Intelligent Alarm Processing: From Data Intensive to Information Rich

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Abstract

The requirement for power system operators to respond more efficiently to the stressed power system conditions that may create large number of alarms asks fort advanced alarm processor that can help operators recognize the nature of disturbance quickly and reliably. Many of the conventional alarm processors lack the ability to analyze complex events efficiently within a time constraint. This paper present two novel intelligent alarm processing options. One is a Fuzzy Reasoning Petri-nets diagnosis model which takes advantages of both expert system and fuzzy logic, and the other is an advanced alarm processor that combines alarm processing techniques at both the substation automation system (SAS) and energy management system (EMS) level. Simulation and test results have demonstrated the effectiveness of the proposed alarm processor options.

1. Introduction

As the power system get operated closer to the limits and operating conditions get more complex , operators are often overloaded with tremendous number of alarm messages generated by the events in the system. A major power system disturbance could trigger hundreds and sometimes thousands of individual alarms and events [1]. Some estimates of the maximum number of alarms which could be triggered by several types of events have been established for the regional control centers of Hydro Quebec [2]:

- Up to 150 alarms for a transformer fault
- Up to 2000 alarms for a generation substation fault, the first 300 alarms being generated during the first five seconds
- Up to 20 alarms per seconds during a thunderstorm
- Up to 15,000 alarms for each regional center during the first five seconds of a complete system collapse

Obviously this is beyond the capacity of any operators to handle quickly and reliably. Thus, under stressful conditions operators may not be able to respond to the unfolding events in a timely manner, and even worse, the alarm interpretation by the operators may be either wrong or inconclusive.

Nowadays, many supervisory control and data acquisition (SCADA) systems have already employed Intelligent Alarm Processing (IAP). The past work [1-4] seems to point out that an intelligent alarm processor that can analyze large number of alarm messages efficiently and extract information that explains the network events quickly is utilizing experts systems and/or fuzzy logic techniques [4,5] to improve processing of data from either SCADA system or from substation intelligent electronic devices (IEDs) [6] . A consensus is that the intelligent alarm processors need to meet the following requirements [7]:

- Reduce the number of alarms presented to the operator
- Convey a clearer idea of the power system condition causing the alarms
- Recommend corrective action to the operator if such action is needed

These goals are clearly not independent. An effective reduction in the number of alarms cannot be achieved just by reorganizing the overall list of alarms into categorized lists that contain smaller number of related alarms. More informative messages must be generated by combining simpler messages. Reciprocally, if a better description of the problem affecting the power system is displayed for the operator, there is often no need to present all the details. Finally, recommending a corrective action is not possible until the problem has been fully understood and explained.

The goal of this paper is to emphasize the difference between displaying raw alarm data vs extracting features from the raw data that will convey information about cause-effect relationships leading to assertion of alarms. To be effective, the new approach has to be automated so that alarm processing and analysis can be performed quickly allowing operators to make timely decisions.

This paper deals with novel techniques for achieving efficiency and speed in alarm processing developed by using additional data obtained from substation IEDs. The background section points to different approaches used by others so far and introduces two new approaches that demonstrate significant benefits. The Solution A is discussed in the next section followed by the Solution B in the subsequent section. For each of the solutions, data requirements, implementation issues, test results and deployment strategy are discussed. The paper ends with conclusions, acknowledgements and list of references.

2. Background

Since the late eighties, the concepts of filtering and suppressing alarms have been used in many practical systems [8]. This was achieved using intelligent techniques. The major intelligent techniques used so far include:

a. Expert System (ES) technique

Expert system (ES) technique [9-12] is well suited for a diagnosis problem like fault section estimation because it mimics the behavior of fault analysis experts which perform fact-rule comparisons and search consequent steps. The disadvantage is that an expert system has to be developed using formalized knowledge that correctly captures the expertise, which may require an extensive expert interviewing effort.

b. Fuzzy Logic (FL) technique

FL technique [13, 14] offers a convenient means for modeling inexactness and uncertainties, hence a powerful solution to handle the imprecise and incomplete data may be implemented. The disadvantage is the need to have empirical data that helps determine the membership function and properties of fuzzy variables.

c. Petri-nets (PN) technique

Petri-nets (PN) based technique [15-18] possesses the characteristics of graphical discrete event representation and parallel information processing. While very fast, the dynamic nature of the temporal change of the alarms cannot be easily captured with the standard Petri-net approach unless further adjustments are made.

d. Fuzzy Reasoning Petri-nets (FRPN) technique

Fuzzy Reasoning Petri-nets **(**FRPN) technique [19-21] gains the advantages of Expert System and Fuzzy Logic, as well as parallel information processing. Some of the disadvantages of previously mentioned individual techniques may be offset by the benefits coming from combining the techniques.

An implicit disadvantage of the traditional knowledge-based systems is that they may be incapable of handling complex scenarios that are not encountered during knowledge acquisition, implementation, or validation. They may also suffer from the slowness in analysis due to involved knowledge representation and inference mechanism. Solutions based on discrete event view of Petri-nets also have several limitations. For instance, the number of initial inputs is limited and it is difficult to model inexactness and uncertainties. Consequently, to accurately identify fault sections under complex circumstances, substantial heuristic rules and information are additionally required.

The sponsors of the studies that resulted in the solutions reported in this paper have engaged in projects to obtain a recommendation how to improve the existing solution, and better understand what it would take to achieve the following goals [22]:

- Analyzing contingencies faster and with more confidence
- Utilizing more redundant data to enhance existing data and conclusions
- Dealing with overwhelming amount of alarms by classifying them according to the causes
- Archiving field data for future analysis of disturbances and related operator actions

This paper provides two novel IAP options to solve the mentioned problems. Firstly, an optimal design of a structure of FRPN diagnosis models is proposed to take advantage over the structure adopted in [23]. This algorithm is exemplified by matrix rule representation and reasoning execution for an FRPN diagnosis model which takes data from remote terminal units (RTU) of SCADA, as well as relay trip and logic operand data from digital protective relays as additional inputs to enhance the estimation accuracy. Secondly, in order to investigate the deeper cause-effect relationship at the substation level, an advanced alarm processor that combines alarm processing techniques at both the substation automation system (SAS) and the energy management system (EMS) level is introduced. The SAS level alarm processor aims at more accurate analysis of substation-wide events using the extra substation measurement data that are not available at the EMS level. The EMS level alarm processor emphasizes the idea of correlating results of analysis of events from different substations to generate explanation for system-wide scenarios.

The concept utilized to achieve the above improvements suggests integrating operational (SCADA) and non-operational (substation IED) data [24]. This new concept is made possible by implementing software for automated analysis of substation IED data turning it into valuable on-line information [25]. The difficulty in deploying this concept is not necessarily related to developing new information processing applications since the mentioned software has been demonstrated [24,25]. The real challenge is to get coordination between different utility groups such as operators, protection and maintenance staff, as well as the IT support teams to make sure the IED data acquisition is fully automated and extracted information is quickly communicated to higher levels in the processing hierarchy. Special attention needs to be given to the use of Global position System (GPS) of satellites for synchronized sampling and time stamping [26].

3. Solution A: FRPN Diagnosis Model

FRPN takes advantages of Expert System and Fuzzy Logic, as well as parallel information processing to solve the problem of fault section estimation. It has been proven that the logic operand data of digital protective relays can be used as additional inputs to enhance the alarm interpretation.

3.1 Data Requirement

Detailed algorithm description of FRPN can be found at reference [3]. The field data needed for this application is listed in Table 1.

Table 1. Data List for Option A

Data from RTU of SCADA (Main data)	
1	CB status change alarms (Opening and Closing)
2	Trip signal of Main Transmission Line Relays
3	Trip signal of Primary Backup Transmission Line Relays
4	Trip signal of Secondary Backup Transmission Line Relays
5	Trip signal of Bus Relays
Data from Digital Protective Relays (*Additional data, in the form of logic operands)	
1	Pickup & Operation signals of Main Transmission Line Relays
2	Pickup & Operation signals of Primary Backup Transmission Line Relays
3	Pickup & Operation signals of Secondary Backup Transmission Line Relays
4	Pickup & Operation signals of Bus Relays

3.2 Implementation

A 14-bus power system shown in Fig.1 is used for the study of fault section estimation problem. The system consists of 34 sections, including 14 buses and 20 transmission lines. The buses are denoted as Bnn. The transmission lines are denoted as Lnnmm.

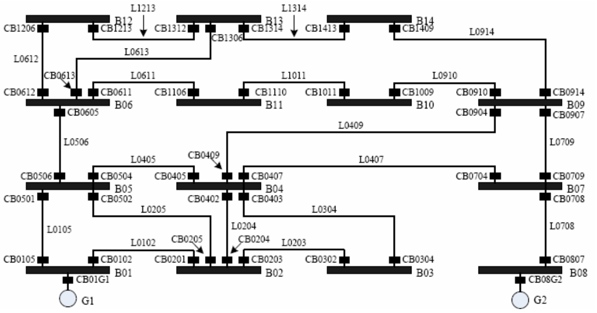

Fig.1. A 14-bus power system model

We use backward reasoning concept to structure the FRPN diagnosis models and generalize the design for transmission lines and buses [4]. The 'AND-OR' structure concisely represents all the possible combinations of main, primary backup and secondary backup protection operations for inferring a fault.

Based on the proposed structure, all the FRPN diagnosis models are developed. Each model establishes reasoning from a set of SCADA data to the conclusion of fault occurrence on its associated section with certain truth degree value. In case of single fault, the conclusion with the highest truth degree value is the final conclusion. As an example, Fig. 2 shows the FRPN models for the transmission line L1314.

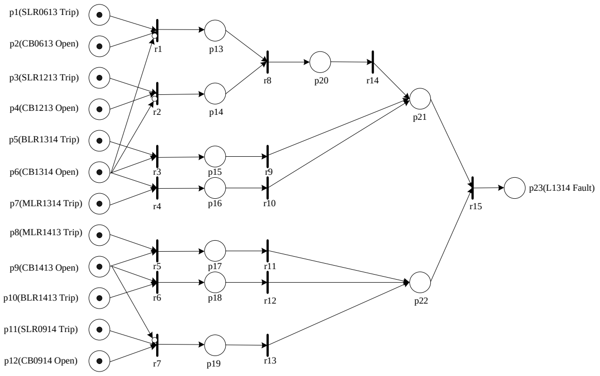

Fig.2. A FRPN model for L1314 fault based on SCADA data

In a digital protective relay, the pickup and operation information of protection elements is usually in the form of logic operands. The relay operands are more reliable than SCADA data because they are more redundant and have less uncertainty than relay trip signals and circuit breaker status signals. They can be utilized to improve the accuracy of fault section estimation based on SCADA data, as shown in Fig.3. When a fault occurs on the transmission line L1314, its associated protection system operated to respond to the fault. In addition to the observed SCADA data, the following relay signals are also observed: SLR0613 Pickup, SLR0613 Operation, SLR1213 Pickup, SLR1213 Operation, BLR1314 Pickup, BLR1314 Operation, MLR1314 Pickup, MLR1314 Operation, MLR1413 Pickup, MLR1413 Operation, BLR1413 Pickup, and SLR0914 Pickup. Since the relay data are more reliable than the SCADA data, they are given a larger truth value 0.98.

If MLR1413 Trip is missing in the SCADA data due to data transmission error while MLR1413 Pickup and MLR1413 Operation are observed, the conclusion will be that a fault occurs on the transmission line L1314 with a truth degree value 0.827.

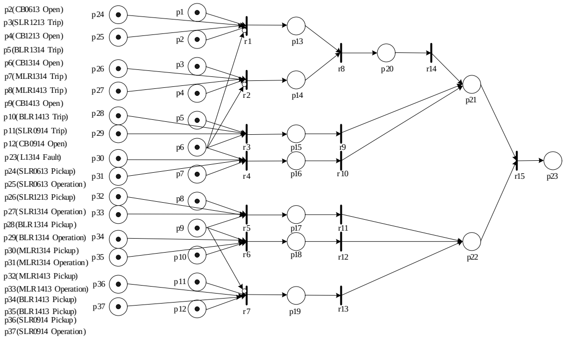

Fig.3. A FRPN model for L1314 fault based on SCADA and digital protective relay data

3.3 Case Study

Based on the approach introduced in [3], a power system/protection system interactive simulation environment for the case study has been developed. The evaluation environment enables one to set up fault scenarios, insert user-defined errors, and generate SCADA data and relay data.

Assume that a permanent fault occurred on the bus B04 at 0.05 second. A second permanent fault occurred on the bus B09 at 0.09 second. All the protection devices operated correctly. No false data occur. The observed SCADA data are listed in Table 2. The observed relay data are listed in Table 3.

Based on the SCADA data in Table 2, the candidates for the fault section are listed in Table 4. Based on both the SCADA data in Table 2 and relay data in Table 3, the candidates for the fault section are estimated and the results are listed in Table 5.

As shown in Table 4 and Table 5, besides the bus B04 and the bus B09, on which faults actually occur, the transmission line L0409, which has no fault, is included in the candidate set. The transmission line L0409 has a far smaller truth degree value than the other two candidates, which indicates small possibility of fault occurrence. The truth degree values of the candidates based on both the relay data and SCADA data are higher than those based on only the SCADA data.

Table 2. SCADA data

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.1000	BR04 TRIP
2	0.2000	CB0402 OPEN
3	0.2000	CB0403 OPEN
4	0.2000	CB0405 OPEN
5	0.2000	CB0407 OPEN
6	0.2000	CB0409 OPEN
7	0.2000	BR09 TRIP
8	0.2000	CB0904 OPEN

Table 3. Relay data

Sequence No.	Time Stamp (Sec)	Observed Signal
1	0.0662	SLR0409
2	0.0677	SLR0709
3	0.0693	BLR0910
4	0.0698	MLR0910
5	0.0703	MLR1009
6	0.0703	BLR1009
7	0.0703	SLR1110
8	0.0724	SLR1409

Table 4. Candidates for estimated fault sections based on SCADA data

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.855
2	B09	0.855
3	L0409	0.513

Table 5. Candidates for estimated fault sections based on SCADA data and relay data

Candidate No.	Fault Section	Truth Degree Value
1	B04	0.882
2	B09	0.882
3	L0409	0.618

3.4 Deployment Strategy

The fault section estimation application may be implemented in a control center to assist the system operator in rapidly identifying faulted sections for restoration process, as shown in Fig.4.

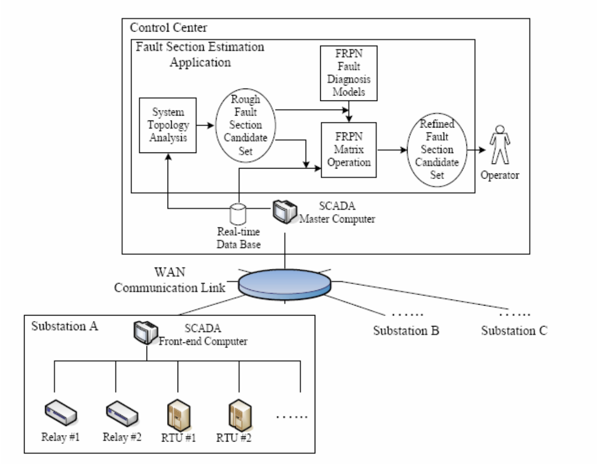

Fig.4. Overall Implementation Structure

The fault section estimation application includes two stage analyses.

- *First Stage*

The system's topology is analyzed based on circuit breaker status data from the real-time data base. The analysis includes all sections isolated by the opening of circuit breakers into a rough candidate set. The set is rough because it may include sections which are not faulted but are isolated due to backup relay operation.

- *Second Stage*

The Fuzzy Reasoning Petri-net diagnosis model as well as data in the real-time data base corresponding to each section in the rough candidate set is used and Fuzzy Reasoning Petri-net matrix operation is implemented. As a result, each section will be associated with a truth degree value. The section with a truth degree value greater than a certain threshold will be included in the refined candidate set. Such a refined candidate set is presented to the system operator for decision-making

In such a solution, the FRPN models which are represented by various matrices are separated from FRPN matrix operations. This is analogous to an expert system whose rule base is separated from its inference engine. The FRPN models can be built in advance based on power system and protection system configurations and stored in files. In such a way, the FRPN models can be easily modified according to the changes of input data as well as power system and protection system configuration.

4. Advanced Alarm Processor using Two-level Processing Structure

The task of this solution is to look into additional substation IED data and develop the cause-effect reasoning.

The proposed alarm processor approach [6] includes two modules, one at the substation and one at the system level respectively. A two-level structure is introduced to effectively use the enormous amount of data available at the substation automation system (SAS) level. Not all that data are directly transmitted to the control center.I Instead, local processing at the computers in substations is carried out and the results of such analysis are transmitted to assist the energy management system (EMS) level alarm processor.

4.1 Data Requirement

Detailed description of field data needed for this application is listed in Table 6.

Table 6. Data list for option B

Data from RTU of SCADA	
1	CB status change alarms (Opening and Closing)
2	Over-current alarms
3	Over-voltage alarms
Data from Local Substation IEDs	
1	CB status measurements
2	Transmission line analog measurements
3	Relay operation data

4.2 Implementation

The proposed alarm processor is developed using a simulation environment as shown in Fig.5. The simulation environment aims at simulating what typically exists in EMS and SAS systems (shown on the left side), and having the proposed new processing as natural extensions (shown on the right side). The substation measurement data simulator is developed using ATPDraw software [27] and Java program code to simulate the IEEE 14-bus system. The results of the data simulator are data files in common format for transient data exchange (COMTRADE) [28]. The simulation results go into the RTU data simulator, which generates snapshots of the phasor values of the analog measurements and the status values of the digital measurements. These values are processed by the alarm simulator, which detects over-limit values or changes of status and creates alarm messages. In this context, the alarm simulator represents the combined role of data acquisition and basic alarm processing at control centre. The alarm messages are then passed to the EMS-level alarm processor, where important alarms indicating a contingency are filtered out and suspicious substations involved are identified. A command is then sent to the corresponding SAS level alarm processors requesting further investigation of the substation measurement data. The SAS-level alarm processor analyzes the COMTRADE files created by the substation simulator for measurement data and sends back its conclusions to the EMS-level, where information from multiple substations is merged and system-wide scenarios are analyzed.

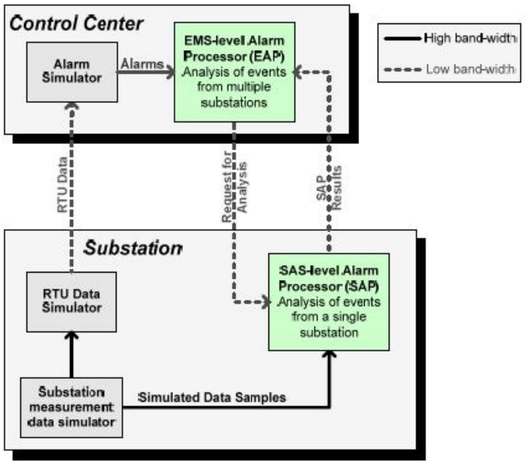

Fig.5. Overall Software Structure

4.3 Case Study

Fig.6 shows the detailed substation configuration diagram for Substations 6 and 13 in the IEEE 14-bus system ATP simulation model. Branch 0602-1305 connects the two substations. Three current sensors (CT1301, CT0601 and CT0602) are placed in these two substations and their measurement data are made available to the EMS level by the RTU data simulator. It is assumed that digital relays capable of recording relay signals are available in both Substation 6 and 13 and these relay signals are simulated by the substation measurement data simulator.

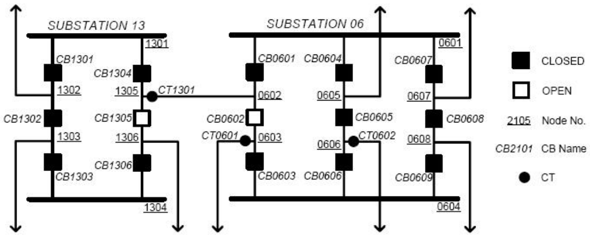

Fig.6. Diagram of Substation 6 and Substation 13 in the IEEE 14-bus system

The following events are simulated:

Case 1: A three-phase fault occurs in the middle (50%) of branch 0602-1305 on Mar 01, 2007 at 00:00:01.000.

Case 2: Transmission line relays in both substations successfully detect the fault and issue trip signals to corresponding CBs 0.1 second later.

Case 3: CB0601 opens immediately. CB1304 does not open.

Case 4: Breaker-failure relay in Substation 13 then issues trip signal to CB1301 after 0.5 second.

Case 5: CB1301 opens immediately and branch 0602-1305 is disconnected.

Table 7 shows the simulated alarms messages from Substation 6 and 13. The result of the EMS-level alarm processor is shown in Table 8.

Table 7. Alarm messages from the alarm simulator

#	Timestamp	Location/ Device	Description
1	Mar 01, 2007, 00:00:01.007	CT1301	Over Current Detected
2	Mar 01, 2007, 00:00:01.008	CT0601	Over Current Detected
3	Mar 01, 2007, 00:00:01.108	CB0601	Circuit breaker opens
4	Mar 01, 2007, 00:00:01.508	CB1301	Circuit breaker opens
5	Mar 01, 2007, 00:00:01.508	CT1301	Current returns to normal level
6	Mar 01, 2007, 00:00:01.508	CT1301	Current is near zero
7	Mar 01, 2007, 00:00:01.517	CT0601	Current returns to normal level

Table 8. Output of the EMS-level alarm processor

Timestamp	Mar 01, 2007, 00:00:01.007		
Analysis Result	Fault detected on branch 0602-1305. Branch 0602-1305 is disconnected by opening CB0601		
Suggested Actions	CB1304 needs to be maintained		
Additional Information (From SAP)	Timestamp	Analysis Result	Suggested Actions
	Mar 01, 2007, 00:00:01.000	Fault detected on branch 0602-1305	(None)
	Mar 01, 2007, 00:00:01.100	Relay issues trip signal to CB0601	(None)
	Mar 01, 2007, 00:00:01.100	Relay issues trip signal to CB0602. CB0602 is already open.	(None)
	Mar 01, 2007, 00:00:01.100	Relay issues trip signal to CB1304. CB1304 does not open.	CB1304 needs to be maintained
	Mar 01, 2007, 00:00:01.100	Relay issues trip signal to CB1305. CB1305 is already open.	(None)
	Mar 01, 2007, 00:00:01.517	CB0601 opens.	(None)
	Mar 01, 2007, 00:00:01.500	Relay issues trip signal to CB1301.	(None)
	Mar 01, 2007, 00:00:01.008	CB1301 opens.	(None)

It can be seen that the proposed alarm processor successfully explained to the dispatcher that over current condition appeared on branch 0602-1305 and the branch was disconnected by relays. It also pointed out that CB1304 did not open successfully to disconnect the branch and maintenance of CB1304 is recommended.

4.4 Deployment Strategy

The two-level alarm processor works on a simulated power system using ATP. Although a real-world implementation is yet to be developed, the applicability issue of the proposed method has been taken into consideration.

- *Data Availability*

Nowadays, more and more IEDs are being installed in the substations. Besides performing their designed functions, these IEDs often record data that can be used for other monitoring and control purposes. For instance, an IED may be capable of recording event reports and analog and binary values similar to disturbance recorders and making it available in real-time.

- *Time Response Issue*

Although the two-level alarm processing structure incurs delay in analysis due to the need of IED data retrieval and telecommunication, the length of delay is usually still acceptable. The initiation command of SAP and the data transmission of SAP results back to the control center are expected to take only a few seconds. While waiting for the results from SAPs, the EMS-level Alarm Processor (EAP) can show the preliminary analysis results done at the EMS level on time-sensitive alarms. After the SAP results arrive, they may replace the original simple alarms with a single one that gives the consolidated information on what happened.

The most important difference of the proposed alarm processor from the existing ones is its idea of looking into substation IED data to support additional reasoning. Most existing alarm processors use different approaches to suppress the number of alarms prompted to the dispatcher and analyze the sequence of events based on the information available in the alarm messages. Although many alarms are recorded in the control center during an event, they are usually received independently from different measuring devices and the correlation of different alarms to a specific event often imposes a hard task. This can be easily overcome by providing GPS synchronization at the source of data, which makes correlating the alarms to the originating event quite easy [26]. By creating a two-level analysis structure and using the substation IED data as a source of information, the analysis becomes much efficient, mainly because the additional amount of information available.

5. Conclusions

This paper firstly reviews the existing research on Intelligent Alarm Processing, and points out the disadvantages on the conventional approaches. They mostly rely on direct representation of raw alarm points, which becomes overwhelming to observe and interpret when operating the system under stressed conditions. This requires implementing new alarm processor to help the operator deal with the tremendous amount alarms by effectively converting raw data to useful information. Two novel Intelligent Alarm Processing options are proposed to illustrate the new possibilities coming from integrating operational and non-operational data in real time.

The FRPN diagnosis model is analogous to an expert system whose rule-base is separated from its inference engine, which can be built in advance based on power system and protection system configurations and stored in files. In such a way, the FRPN models can be easily modified according to the changes of input data as well as power system and protection system configuration. This solution uses primarily SCADA data and does not need detailed data from substation IEDs except trip and logic operand information from protective relays.

In the second proposed approach, two-level processing structure includes Energy Management (EMS) and Substation Automation System (SAS) solutions. The SAS-level alarm processor uses measurement data that are only available within the substation and is capable of recognizing the nature of disturbance in the substation. More detailed analysis functions can be finished in reasonable time by converting data into information at the data source. The dispatchers are prompted with more useful and distilled information, including suggested actions to be taken.

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